Hamilton Street Railway Compressed Natural Gas Bus Demonstration Project – Final Report on Phases 1-3

Ontario
Ministry of Transportation
Transportation Technology and Energy Branch

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Hamilton Street Railway Compressed Natural Gas Bus Demonstration Project – Final Report on Phases 1-3

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EXECUTIVE SUMMARY

The Hamilton Street Railway (HSR) has completed a 3 phase demonstration of the feasibility of operating compressed natural gas (CNG) buses in transit service in a program financed by HSR, Energy, Mines and Resources Canada, the Ontario Ministry of Energy, the Ontario Ministry of Transportation and Union Gas Ltd.

Objectives of the Demonstration

The principal objectives of the 3 phase demonstration were to:

- select the engine and CNG components and manufacturers
- convert one bus to CNG and demonstrate compliance of the prototype bus with a set of fuel economy and performance standards
- complete the conversion of a total of 6 CNG buses
- install and operate a CNG refuelling facility
- obtain data on the costs, performance and reliability of the CNG system
- define the changes in the engine, bus and refuelling system needed for revenue service operation of a CNG bus fleet in the future
- communicate the findings to the transit bus community.

Outcome of the Demonstration

The objectives of the demonstration were met.

The demonstration monitored the conversion by HSR staff of six 1977 "New Look" model General Motors diesel buses to CNG over the period October 1985 to September 1987. The conversion used spark-ignition CNG engines prepared by Iveco (Fiat) and a fuel storage system comprising 7 fibre-wound aluminum CNG storage cylinders and other in-vehicle equipment.

The CNG buses were fuelled from a 200 cubic feet per minute, 150 hp compressor installed at the HSR Wentworth Street garage and operated over 245,000 km under regular service conditions. The requirements for a 5-minute bus refuelling operation were identified.

The CNG buses performed at least as well as diesel buses of the same model and year, although range was limited in severe winter conditions. The safety record and driver acceptance were excellent.

The demonstration defined the technical requirements and improvements which should be incorporated in future designs of CNG buses to improve engine durability and ease of maintenance.

Fuel utilization tests and current costs for natural gas and diesel fuel indicate that the CNG bus will provide transit service at a lower fuel cost than the current technology diesel bus. Fuel costs in the CNG bus will be substantially lower than those in diesel buses which will be sold in the U.S. and Canada after 1990 when low sulphur, low aromatic diesel fuel and/or particulate trap technologies will be employed to meet the post-1990 bus emission standards.

The <u>total</u> cost of operation of the prototype fleet CNG buses, including the cost of retrofitting existing diesel buses to operate on CNG, was higher than that of the standard diesel bus fleet in the demonstration period. The technical changes in the CNG bus and changes in the refuelling system defined in the demonstration offer the prospect of lower total costs for CNG buses than the diesel buses operated in the future at HSR. The equipment and engine setup needed to control NOx and hydrocarbon emissions to comply with the anticipated post-1990 urban bus emission standards was identified. The low particulate emissions of the CNG engines were verified.

Recommendation

It is recommended that these improvements be incorporated in an expanded fleet of CNG buses and the performance and costs of the fleet be measured in 2 years of revenue service operation.

1. INTRODUCTION

1.1 Status Summary

Hamilton Street Railway (HSR) has successfully completed a technical demonstration of the feasibility of using compressed natural gas (CNG, also termed NGV - natural gas for vehicles) as a fuel for transit buses.

The preliminary work has demonstrated the following:

- Existing GM diesel-powered transit buses can be refitted in-house with a natural gas engine, compressed gas storage tanks and ancillary equipment. Six diesel buses were converted in this way during the period October 1985 to September 1987. Equipment and conversion costs need to be reduced before retrofitting becomes a practical route to CNG buses.

- CNG buses can be safely refuelled from an on-site refuelling facility on company-owned property. The 6 buses in the demonstration have been refuelled with about 194,500 m3 of gas, equivalent to substitution of about 141,300 litres of diesel fuel in the period to 30 June 1988.

- CNG buses can be operated throughout the HSR transit bus system. 245,000 km. of CNG vehicle operations were recorded in the period October 1985 to 30 June 1988.

- Public and driver response to the CNG buses is favourable.

- There is great interest among other bus properties in the adoption of the CNG bus if favourable economics of operation and reliability in revenue service can be demonstrated.

- Technical improvements can be made in the future to the CNG engine gas storage and refuelling system to improve CNG bus reliability, range, operating and maintenance costs.

1.2 Background and Rationale

In 1984 HSR investigated trends in diesel fuel price, supply and quality and concluded that an investigation of alternatives to diesel fuel should be undertaken. HSR has extensive experience with trolley buses but decided also to explore alternative internal combustion engine fuels. This led to the selection of natural gas as the alternative fuel and spark-ignition as the engine technology. Natural gas was chosen because of the large supplies available in Canada and the anticipation that the price of Canadian natural gas would not increase at the same rate as that of the imported crude oil necessary to produce a significant part of the high quality diesel fuel required in Canada. The demonstration of CNG at HSR was undertaken at a time when similar demonstrations were being undertaken at other Canadian properties using propane and methanol fuel and engines.

The decision to use CNG was also made in light of the substantial financial incentives available from the federal and Ontario governments and which still apply, namely, there is no federal sales or excise tax on CNG, but taxes are levied on diesel fuel. The government of Ontario levies no sales tax on CNG but taxes diesel fuel and the Ontario sales tax would not apply to purchase of CNG buses.

While there was experience in the use of CNG in automobiles, small trucks and some school buses, and of propane in these types of vehicles and transit buses (in Ottawa and Vienna), no experience existed in the production or use of CNG-fuelled buses. Accordingly, HSR in association with the Ontario Ministries of Energy and Transportation, Energy, Mines and Resources Canada, and Union Gas (the gas utility in the Hamilton area), decided to undertake a stepped demonstration program to provide

the information and experience necessary to permit HSR and other bus properties to make a decision on the economic, technical and operational viability of CNG as a transit bus fuel, particularly with respect to the continued use of diesel buses.

Another factor involved in the decision to undertake the demonstration was the anticipated environmental benefit that would be available from the replacement of diesel-fuelled buses with low exhaust emission CNG buses in the high-density areas which could not be served by trolleys. During the course of the demonstration public awareness of the environmental impact of diesel-fuelled vehicles has increased and legislation developed which will sharply curtail the particulate (smoke), nitrogen oxides (NOx), carbon monoxide (CO) and unburned hydrocarbon emissions (UHC) from heavy-duty vehicles.

Use of CNG-fuelled vehicles appears to offer a feasible and economic route to these environmental standards and benefits.

1.3 Unknown Factors

The proposed demonstration program recognized the need for innovative solutions to a number of unknowns:

- no CNG bus or commercial CNG engine was available from manufacturers
- no experience existed on the use of CNG conversion equipment in a demanding transit bus application
- vehicles dedicated to CNG (as distinct from dual-fuel vehicles) had only been used in short range applications compared to the 300-500 kilometer daily range required in transit buses; a range problem had therefore to be overcome and be accomplished within restrictions on the weight of the vehicle and the location of CNG storage tanks
- fast refuelling times (less than 5 minutes) are mandatory for

buses (current refuelling practice did not provide fast fuelling)

- a special problem to be overcome in Hamilton was that fully-loaded buses were required to be comparable in performance to diesel buses in service over routes which include a 7% gradient
- little experience existed on the safety of CNG buses
- driver and rider response were uncertain.

Information was also sought on:

- the cost of natural gas from the utility and after compression
- CNG vehicle fuel consumption
- economic viability of CNG systems (capital costs, vehicle conversion costs, operating and maintenance costs).

The demonstration was therefore required to provide many different types of information and to generate experience and expertise among a number of HSR employees and suppliers. The decision was therefore made to conduct the preliminary investigation in 3 phases:

Phase 1: Project Feasibility
Phase 2: Demonstration of System Operability
Phase 3: Definition of Critical Requirements for Revenue Service Operation.

A successful outcome of Phases 1-3 was anticipated to lead to a long-term program involving use of a significant number (10 or more) of CNG buses in revenue service to demonstrate and report the economic and environmental benefits of the CNG fuel/vehicle system to the extent that HSR and other bus properties may consider the inclusion of CNG buses in their future acquisitions.

1.4 Objectives

The overall objective of the 3 phase demonstration program was to

demonstrate the economic and technical viability of natural gas by operating 6 CNG-fuelled buses in revenue service with on-site refuelling for a period of at least 2 years during which time the operation of the CNG bus fleet and a set of matched diesel-engined buses was to be monitored and compared.

The goals set for the 3 phases are summarized in Exhibit 1.

The contracts between HSR, Union Gas and the supporting government agencies established a series of tasks, technical specifications for the engine, engine controls and refuelling system, schedules and reporting procedures.

The key tasks are summarized in Exhibit 2.

Exhibit 1

Demonstration Goals and Status

GOALS	STATUS AT 30.7.88
PHASE 1	
Select engine and CNG component manufacturers	Iveco 8220 engine chosen and CNG Cylinder Corp. tanks
Convert 1 bus to CNG	Completed with full documentation
Conduct GO/NO-GO test of prototype CNG bus	Test successful on CNG
Compare CNG bus with current and 4-stroke diesel bus	Iveco diesel unsatisfactory: withdrawn from program
Demonstrate refuelling	Refuelling at Union Gas commercial stations demonstrated
Purchase engines and components for Phase 2	Orders placed for engines and components
PHASE 2	
Install refuelling facility	Union Gas compressor installed and operated at Wentworth St.
Complete conversion to 6 CNG buses total	Total of 5 converted to CNG
Revenue service operation	Tripper service (½ day)
Survey drivers	Positive response
PHASE 3	
Obtain data on costs, reliability in revenue service	Completed conversion to 6 CNG buses. Winter/summer data obtained Fuel data limited to fleet total (equipment limited)
Optimize CNG bus for reliability, performance	Availability equal to diesel buses demonstrated. Current equipment deficiencies defined
Support engine optimization work	Optimum engine configuration for fuel economy and pollution control defined by work at ORF
Define future CNG bus requirements	Requirement for expanded fleet and Phase 4 defined
Communicate findings to the transit community	Information transfer and communications established
PHASE 4	
While under review 6 buses continue in revenue service	

Exhibit 2

Key Tasks

TASKS	STATUS
Identify bus configuration	Retrofit of existing GM "New Look" buses selected
Identify engine technology and supplier	Iveco CNG spark-ignition engine selected
Design engine installation	Engine cradle and other components designed and fabricated
Purchase engines	6 CNG engines, 1 diesel and spares purchased from Iveco subject to approval in GO/NO-GO test
Design fuel tank configuration in bus	7 fibre-wound tanks per bus
Purchase CNG cylinders and accessories	42 cylinders purchased from CNG Cylinder Corp.
Convert 2 buses	1 to CNG and 1 to 4-stroke diesel
GO/NO-GO test of prototype bus	Decision to proceed
Complete bus conversion equipment acquisition	Completed
Convert 5 buses in-house to CNG	Completed over 24 month period
Operate fleet of CNG buses	250,000 km in CNG buses, 4-stroke diesel discontinued
Design and install compressor stations	Connected and operated for 27 months. Continues in operation
Train staff for maintenance and operation	Experienced and trained staff now available at HSR
Safety training	HSR staff, local fire departments trained
Equip garage for testing, maintenance of CNG buses	Equipment installed, procedures are now routine
Conduct comparative evaluation of alternative fuel engines	Completed, report issued by ORF
Optimize CNG engine	Preliminary report issued by ORF/MTO
Conduct rider and driver survey	Information obtained with informal survey
Collation and reporting data	Final report issued. Data limited by equipment decisions
Transfer technology to other properties/publicity	Active program continues
Assess future bus operation at HSR	Medium term program at HSR determined

2. ORGANIZATION AND FUNDING (see Exhibit 3)

2.1 Project Management

2.1.1 Steering Committee

A Steering Committee was established to provide overall direction to the demonstration. Membership of the Steering Committee was as follows:

General Manager of HSR	Chairman
Director of Engineering/Operations, HSR	Project Manager
Energy, Mines and Resources Canada (EMR)	2 representatives
Ministry of Energy, Ontario (MOE)	1 representative
Ministry of Transportation, Ontario (MTO)	1 representative
Union Gas Ltd.	1 representative

The committee reported to the Hamilton-Wentworth Regional Council and to the government funding and supporting agencies through the Chairman.

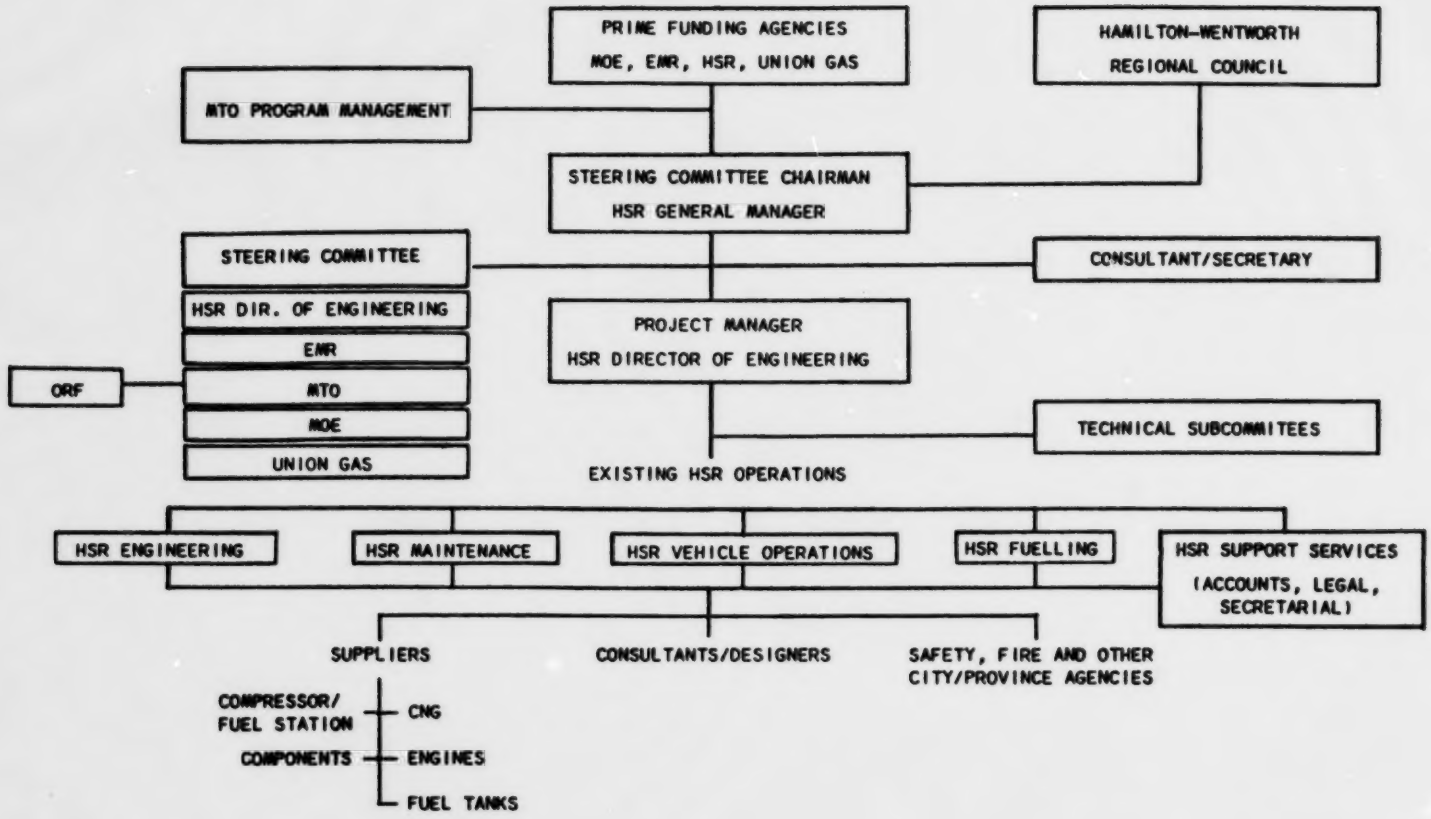
The Steering Committee was assisted by a consultant/secretary who attended all meetings and by technical specialists from the Ontario Ministry of Transportation and Union Gas who attended meetings as observers at the invitation of the Chairman.

Technical subcommittees were convened to resolve and report on specific technical issues and in 1988 a technical subcommittee was formally established comprising 2 members from HSR (Project Manager and CNG bus technician), 2 from the MTO (transportation and engine specialists), and from Union Gas (CNG technical specialist).

Exhibit 3 illustrates the organization of the demonstration.

Exhibit 3

Organization for CNG Bus Demonstration



2.1.2 Operations

MTO provided management assistance at the total demonstration level and HSR provided the operating management and staff for the project. The CNG demonstration bus operations were conducted as part of normal transit bus operations at HSR with the addition of a full-time technician dedicated to the testing, conversion and maintenance of the CNG fleet. Specialists from MTO assisted HSR in special technical matters and in liaison with other technical groups such as the Ontario Research Foundation (ORF) and the Ottawa-Carleton Regional Transit Commission (OC Transpo). Union Gas provided assistance in the initiation of the first CNG fuel system in the bus and in engineering and maintenance of the natural gas compressor/refuelling station.

All parties to the demonstration agree that the organization and management of the project were appropriate and productive.

2.2 Financing of the Demonstration

The 3 phase demonstration was cost-shared by EMR Canada, MOE, Union Gas and HSR. The budget and expenditures for the 3 phases completed in March 1988 totalled $710,500 as follows:

Phase 1: $468,000
Phase 2: 181,500
Phase 3: 61,000

In addition MTO and EMR jointly funded certain subcontracts for work carried out at ORF involving the comparative evaluation of the Iveco CNG engine, a corresponding Iveco propane engine, special Iveco 4-stroke diesel engine, a methanol engine (M.A.N.) and the Detroit Diesel Allison conventional 2-stroke diesel engine, and preliminary work on the optimization and pollution control of the Iveco CNG engine.

3. TECHNOLOGY AND SUPPLIER SELECTION

3.1 CNG Bus Acquisition Strategy

In 1985 when the search for appropriate bus acquisition strategies was undertaken, no manufacturer of transit buses was able to supply buses equipped with a CNG engine. Limited experience was available at M.A.N. on the conversion of M.A.N. 4-stroke diesel-engined buses to use of liquid natural gas and OC Transpo (Ottawa) had initiated a propane bus demonstration based on the retrofitting of existing GM buses with prototype propane engines produced by Iveco (a division of Fiat). In view of the timing and the probable need for extensive crash testing on new CNG buses it was decided to extend the Iveco/OC Transpo technology to CNG namely to purchase prototype CNG engines and to retrofit 6 existing GM 1977 model year "New Look" buses from the fleet. This involved the conversion of 4-stroke diesel engines to spark ignition engines using a gas carburetion system, reversal of the engine direction of rotation to provide engine compatibility with the Allison V730 transmission in the GM buses and the installation of gas storage cylinders.

An alternative conversion technology in which CNG is added to a compression ignition diesel engine to produce a dual fuel engine was considered to be insufficiently developed. The technology has since been applied in prototype dual-fuel transit buses operated in Vancouver and Tacoma, Washington.

3.2 CNG Spark Ignition Engines

All N. American manufacturers of heavy duty highway diesel engines and selected European companies with gas engine experience were invited to bid on the supply of engines and service.

No North American engine manufacturer was able to supply the CNG

engines and only the Iveco engine appeared capable of being fitted in the GM bus engine compartment in place of the compact 6V71N diesel engine. Accordingly a contract was awarded to Dereco of Arbon, Switzerland (a division of Iveco) for 6 CNG engines based upon conversion of the Iveco 4-stroke, 6 cylinder (in-line configuration), 9.6 litre diesel engine.

The spark ignition system installation was the responsibility of the engine manufacturer but assistance was given by HSR and MTO in the selection and interfacing of the gas let down and mixing system (the gas "carburetion system"). Dereco staff with HSR staff and Hovey Industries of Ottawa undertook the engineering changes needed to the engine cradle, exhaust, air and cooling systems. The outcome is that the engine replacement and installation process is well documented, routine, and similar to that involved when interchanging conventional diesel engines.

3.3 Vehicle Fuel Tanks

The conversion to a mono-fuel CNG bus was accomplished by replacement of the diesel fuel tank with a series of fibre wound aluminum tanks which were manufactured by the CNG Cylinder Corporation of California. No preassembled tank system was available and accordingly HSR, together with the staff of Union Gas, undertook the cylinder installation design and installed the first prototype fuel storage system.

Because of the monocoque design of the GM "New Look" bus it was possible to install 7 of the filament-wound aluminum cylinders (each 13 inch diameter and 72 inches long). Each cylinder had a rated storage capacity of 1,084 standard cubic feet (30.7 cubic meters) of natural gas so that the energy in the 7 storage cylinders would be equivalent to about 200 litres of diesel fuel (about 7.5 GJ of energy in total).

Technical data on the CNG engine and the CNG bus are summarized in

Exhibits 4 and 5.

3.4 4-Stroke Diesel Engined Bus

An Iveco 4-stroke diesel engine of the type used to produce the CNG engine was also reworked by Iveco to provide a counter clockwise rotation (viewed from front) diesel engine compatible with the standard Allison transmission of the GM bus. This was installed in a 1977 "New Look" bus. The objective was to provide a comparison of similar engine sizes and technology and to reduce to a minimum the number of differences between the CNG and diesel buses in the demonstration. The use of the 4-stroke diesel engine was also expected to give useful data on the fuel or energy economy associated with change from a 2-stroke (DDA) to a 4-stroke (Iveco) engine in addition to measuring the energy implications of conversion from diesel fuel to CNG.

3.5 Refuelling Station

The refuelling strategy involved the initial use in Phase 1 of a commercial refuelling facility located in Hamilton at the premises of the supplier of natural gas, Union Gas. Later in the demonstration a dedicated refuelling facility was installed at the Wentworth Street garage of HSR. The water-cooled, 150 hp, 200 cubic feet per minute compressor facility was supplied on loan by Union Gas; HSR provided the foundation, wiring, and a new electrical transformer. Union Gas supplied gas to the facility at a commercial rate. A nominal charge was made for the use of the equipment and provision of maintenance services to HSR. The compressor station was contained within a visual and sound barrier to avoid any public concern and nuisance in this heavily populated area.

The commercial fuelling station provided daily data on the fuel use of each bus during the start-up phase but it was decided not to purchase a $30,000 micromotion meter for installation at the Wentworth

Exhibit 4
Specifications for the Iveco Reverse Rotation CNG Bus Engine
8220.RNG (Data from Dereco Ltd.)

1. ENGINE

Dry weight		800 kg	1764 lbs
Dimensions	Length	1396 mm	54.96 ins
	Width	635 mm	25 ins
	Height	961 mm	37.83 ins
Bore		125 mm	
Stroke		130 mm	
Capacity		9.572 litres	
Compression ratio		12.1:1	
Firing order		1-4-2-6-3-5	
Rotation		Clockwise (view from flywheel)	
Nominal speed		2100 rpm	
Nominal power		127 kw	170 hp
Max. torque		634 Nm,65 mkp	122 lbf/sq in
Speed at max. torque		1000 rpm	
Brake specific fuel consumption	at 2100 rpm	0.210 m3/hp hr (10.2 MJ/kwh)	7.61 MJ/hp hr *
	at 1000 rpm	0.202 m3/hp hr (9.8 MJ/kwh)	7.31 MJ/hp hr
Cylinder pressure (bmep)		840 kPa	

2. VALVE TIMING

Inlet open		9° before Top Dead Centre (TDC)
closed		51° after Bottom Dead Centre (BDC)
Exhaust open		48° before BDC
closed		15.5° after TDC
Valve clearance	Cold engine Inlet	0.25 mm
	Exhaust	0.50 mm

3. PISTON

Type	Similar to Diesel version in general
Combustion chamber	Heron, with a volume of 135.8-140.2 cm3
Piston/cylinder head cold clearance	1.80-1.90 mm

* with test gas 36.23 MJ/m3

Exhibit 4 continued

4. FUEL SYSTEM

Fuel	CNG: test gas with 36.23 MJ/m3
Filter/fuel lock valve	IMPCO VFF 30
Pressure regulators	Tartarini (2 in parallel) 3 stage 43-20-0 psig
Carburetor	IMPCO CAG 425-20-6 (4 holes); cone: V19K
Governor	Holly-base (pneumatic flyweight governor on distributor shaft actuates throttle). A Limitron max speed governor was also added.
Governed speed	2190-2250 rpm

5. IGNITION SYSTEM

Voltage	12V
Electronic box	Bosch 0 227 100 033
Coil	Bosch 0 221 122 303
Distributor	Bosch B 237 360 275
System-drawing	Bosch A 227 019 190
Spark plug	Bosch W2CC
Gap	0.4 mm (max. 0.6-0.7 mm)
Ignition timing 600 rpm	10° CA before TDC

6. INLET/EXHAUST SYSTEM

Exhaust, max. backpressure	60 mmHg
Inlet, max. restriction	400 mmH 0

7. COOLING SYSTEM

Coolant	Min 30% of commercial antifreeze

8. LUBRICATION SYSTEM

Lube oil recommendation	Low ash multigrade oil such as Essolube G-10W-40 (see Dereco Technical Report #184/85, July 12,1985), Essolube G30 (SAE 30), Shell Mysell R30 (SAE 30)

Exhibit 5

Technical Data CNG Prototype Bus

VEHICLE	1977 General Motors "New Look" coach, 50 passenger length 40', width 102", wheel base 285" gross vehicle weight 28,000 lbs.
ENGINE	Iveco, 6 cylinder in line, counter clockwise rotation bore 125mm, stroke 130 mm compression ratio 12.1 horsepower, 170 at 2250 rpm
TRANSMISSION	Allison V730 3 speed automatic
CARBURETOR	Impco CAG 425-20-6 single Venturi 4 barrel throttle plate
REGULATORS	Tartarini (2 in parallel) 3 stage, 43-20-0
GOVERNOR	Holly base 2190-2250 rpm, plus Limitron
IGNITION SYSTEM	Bosch electronic 12 volt timing 10° CA before TDC at 650 rpm
ALTERNATOR	Niehoff, belt drive, air cooled 12 volt, 350 amp
FUEL	compressed natural gas (CNG)
FUEL STORAGE	7 filament wound aluminum cylinders 13" diameter, 72" long capacity 1084 standard cubic ft, each total 7 tanks equals 200 litres of diesel fuel
RANGE TARGET	300 km per refill

Street garage which was required if the CNG transfer to each bus at the garage was to be monitored. Instead the total of uncompressed gas input to the compressor station was monitored using a standard gas meter. Weekly data on the total fleet use of natural gas (including possible small losses in compression and during vehicle refuelling) was therefore obtained during Phases 2 and 3.

The Wentworth St. facility was not designed for fast-fill. Gas was compressed and available at the maximum compression rate of 5.7 cubic meters per minute. Totally fuelling 7 empty cylinders could therefore be done in about 38 minutes but in normal operation a refuelling time averaging 20 minutes per bus was obtained. It was not considered important in the feasibility demonstration to provide cascade storage or higher compressor capacity which would reduce refuelling time. Slow overnight refuelling is unacceptable in revenue service and this option was not considered.

3.6 Natural Gas Quality and Properties

It is important that natural gas used for CNG be low in water, sulphur compounds and other material which may cause corrosion in the compressors and stress-crack corrosion in stationary and in-vehicle storage cylinders. The fuel economy of mono-fuelled CNG vehicles can be high if a high compression ratio engine is used. Use of a high compression spark-ignition engine requires a high octane fuel. It is therefore important to ensure that the very high octane value of methane (the principal constituent of natural gas) of 130 octane is not degraded or varied significantly through addition of higher hydrocarbons which have a lower octane number. A National Standard for natural gas used in production of CNG is under development by the Standards Council of Canada in conjunction with the Canadian Gas Association. The standard is expected to be similar to that given in Exhibit 6 which will define the required composition of uncompressed gas rather than the engine

Exhibit 6
Natural Gas Standard and Quality

	Anticipated Canada Standard*	Supply from Union Gas
Volume (%)		
Methane	80–100	95–96
Ethane	10.5 max.	2
Propane	3.5 max.	0.1
Butanes	1.5 max.	negligible
Pentanes	0.5 max.	negligible
Nitrogen	7.0 max.	1–2
Carbon dioxide	3.0 max.	1
Oxygen	1	negligible
Weight Basis (mg/m3)		
Hydrogen sulphide	22.9	negligible
Total sulphur	460	sulphur containing odourant is added
Water	102	
Energy Basis (MJ/m3)		
Energy content	37.05–42.49	37.65

* Potential listing of anticipated requirements of Canadian standard.

performance of CNG delivered. This differs from the Canadian standard for diesel fuel or gasoline which set performance standards rather than composition due to the high variability in the composition of the conventional fuels, gasoline and diesel. The composition of the natural gas supplied to HSR by Union Gas (see Exhibit 6) was well within the anticipated Canadian CNG standard.

The storage, handling and safety requirements for CNG vehicles differ from those used with diesel due to the great differences which exist between the properties of diesel fuel and CNG. Exhibit 7 summarizes the key properties of diesel fuel and CNG and, to provide a familiar reference, gasoline.

3.7 Tests and Test Equipment at HSR

HSR routinely measures the power output of the diesel buses on a chassis dynamometer. Power measurements are made at selected engine speeds to determine which buses require service. Engines equipped with spark ignition engines also use such an engine dynamometer for power measurement but additional electronic equipment is normally used to measure ignition timing and to optimize the spark advance.

HSR used the existing bus chassis dynamometer and purchased electronic equipment to set up the CNG buses. An exhaust gas analyzer was subsequently added to evaluate the extent of gas combustion in the engine. This permitted engines in the CNG bus to be optimized for power and fuel economy and provided a limited in-house engine performance diagnostic capability. Extensive examination of engine performance ("engine mapping") and exhaust gas analysis requires facilities only available at a few research sites in N. America. Accordingly, engine optimization and comparative engine power and exhaust gas analyses were conducted on engines (not buses) at the Ontario Research Foundation under subcontracts managed by MTO. Engine test data was also provided by the engine supplier (Dereco/Iveco).

Exhibit 7

CNG, Gasoline and Diesel Fuel Properties

PROPERTY	GASOLINE	DIESEL	CNG
Flammability limits (vol. % in air)	1.0–7.6	0.7–5.0	5.3–15.0
Minimum ignition energy in air (MJ)	0.24	0.3 (est)	0.29
Auto ignition temperature (°C)	227–470	245–260	540
(°F)	440–880	470–500	1004
Flash point (°C)	–43	52 (min)	gas
(°F)	–45	125	gas
Energy content, lower heating value (MJ/litre)	31.2–33.0	36.1–37.4	7.84*
(MJ/kg)	41–44	43–44.5	53.4
Diffusion coefficient in NTP air (cm/sec)	0.05	low	0.16
Density of gas relative to air = 1	3.4	>4.0 (est)	0.555
Vapour pressure or equivalent (atm)	0.6–0.8	0.0005	1
Normal boiling point (°C)	30–200	150–380	–161
(°F)	86–390	300–715	–260
Storage conditions (ambient temp)	liquid	liquid	compressed gas**
Octane number, range	87–93	N/A	120–130
Cetane number, average	N/A	40–44	N/A

* Gas at 3000 psig as delivered in Hamilton
** 2400–3000 psig in vehicle (3600 psig bulk storage)

4. ENGINE AND BUS TESTS

4.1 Engine Tests by the Manufacturer

The Iveco 8220.RNG engine tested on the Dereco Ltd. dynamometer using a synthetic natural gas with a slightly lower calorific value (36.25 MJ/m3) than the commercial supply to HSR (37.5 MJ/m3) met the specification set by HSR, which was essentially to meet or exceed the maximum power and acceleration of the DDA 6V71N diesel engine (see Appendix for details).

4.2 Chassis Dynamometer Tests at HSR

A GM "New Look" 1977 vintage bus was re-engined with the prototype Iveco CNG engine and equipped with a fuel system including 7 storage tanks (72" x 13" diameter). The bus was then tested on the HSR bus chassis dynamometer stand and the results compared with those from a typical standard GM "New Look" bus of the same year equipped with C55 injectors and another bus re-engined with the experimental (reverse rotation) Iveco 4-stroke diesel engine.

The CNG, 4-stroke and 2-stroke diesel engined buses provided comparable power output of 100 hp at the wheels when tested at the 40 mph condition with a 30 hp parasitic load (see Exhibit 8). The value at the 40 mph setting (1500-1550 rpm) exceeded the 85-90 hp value normally used at HSR as the limit below which buses are deemed to require service. The high speed performance of the CNG bus was outstanding.

It was concluded that the prototype CNG engine exceeded the minimum specifications.

Exhibit 8

Comparative Dynamometer Tests on CNG and Diesel Buses

Measured Horsepower

Dynamometer Speed Setting	CNG Bus (#7727)	GM 6V71N Diesel (#7711)	Iveco 4-Stroke Diesel (#7708)
15	90	100	70
20	100	100	70
25	100	100	70
30	110	110	80
35	90	110	80
40	100	100	70
45	110	100	70
50	120	90	50
55	130	70	not reported
Weight of Bus (kg)	10,290	9,790	9,810

Notes: All tests conducted with parasitic load of 30 hp (#7727 was also tested with a warm parasitic load of 10 hp).

The net weight difference between the CNG bus and the diesel bus is accounted for as follows:

- the Iveco 8220 engine is lighter than the DDA 6V71N
- the CNG tanks plus fuel weigh more than the diesel tank plus fuel
- the 7 empty CNG tanks, lines and supports weigh approximately 400 kg more than the empty diesel tank and diesel fuel line they replace

4.3 Road and Fuel Economy Tests

A part of the "Go/No-Go" engine acceptance tests involved the demonstration that the CNG bus would not exceed a fuel consumption of 1.5 times that of the standard 1977 GM diesel bus measured on an energy basis. Fuel cost and bus range considerations were involved in selection of the 1.5:1 fuel ratio.

Another requirement was that a fully loaded CNG bus would be capable of climbing a 7% gradient (the "mountain grade" in the Hamilton Wentworth routes) at a speed not less than 20 km/hour (equivalent to that of the average GM bus in service on the "mountain route").

Another requirement was that the loaded CNG bus would have a range between refuellings of not less than 250 km.

The fuel consumption tests involved running the buses at part loading (2200 kg load) over a 130 km circuit containing suburban and downtown routes and the "mountain route". The test conditions (excluding the mountain route) approximate those contained in the standard bus test cycle, the Advanced Design Bus (ADB) cycle. The buses were run in tandem 4 times over the selected circuit to develop the 130 km of test over an elapsed period of 312-314 minutes, including 235 stops.

Key results of the Go/No-Go demonstration were (see Exhibit 9):

- The fuel consumption of the CNG bus was substantially below the Go/No-Go level (1.1 versus the 1.5 max. target).

- The average speed of the CNG bus over the circuit was equivalent to that of the 2-stroke diesel bus.

Exhibit 9
Summary of Road Test Data

	CNG Bus (#7727)	Iveco 4-Stroke Diesel (#7711)
Fuel use over 4 circuits, kg	54.8	56.4
4 Circuit distance measured, km	135.3	130.9
Stops, scheduled & unscheduled	235	235
4 Circuit test duration, minutes	221	222
Average speed made good* km/hr	36.6	35.2
Fuel economy:		
litres/100 km, diesel	N/A	52.56
m3/100 km, natural gas	59.39	N/A

* Speed made good includes all stops from the beginning to the end of the route. Speed made good is an in-service efficiency measurement used in transit system audit and planning operations.

Conclusions drawn from this component of the Go/No-Go test were:

- The CNG bus consumed 1.13 m3 of gas under condition where the 2-stroke diesel bus consumed 1 litre of diesel fuel (i.e. the volumetric fuel utilization ratio: volume of gas in m3/volume of diesel in litres was 1.13 compared to a maximum of 1.5 set for acceptance).

- The range of the CNG bus equipped with 7 fuel tanks charged to 3,000 psig with commercial quality natural gas would be 375 km. The requirement of a minimum range in excess of 250 km was therefore met. (The CNG bus range can be compared with the maximum range of about 500 km available in the HSR diesel buses and the fact that 92% of the diesel bus operations at HSR involve a daily range requirement below 375 km).

- The cost of uncompressed gas would be 55% of the cost of taxed diesel fuel at the prevailing costs.

The bus climb capacity test was conducted with the CNG bus loaded to the equivalent of 73 passengers (3,900 kg total load) run in tandem with the GM 2-stroke bus similarly loaded. The loaded CNG bus was consistently able to climb the 7% gradient at a speed not less than 42 km/hr, substantially exceeding the requirement of not less than 20 km/hr at a bus load of 3,800 kg. Exhibit 9 presents a summary of the road test results.

It was therefore concluded that the CNG bus could be used in revenue service runs with no penalty in terms of route selection (for hill climbing reasons), route time, and passenger carrying capacity. It was further concluded that the CNG bus range was compatible with requirements in normal route service at HSR. The fuel consumption levels demonstrated would not involve a fuel cost penalty in the change to CNG.

The experimental 4-stroke diesel engine from Iveco did not run smoothly over the Go/No-Go test circuit but still showed an 8% economy in diesel fuel use compared to the 2-stroke diesel.

It was concluded that the optimization of the Iveco 4-stroke diesel engine after conversion to reverse rotation was incomplete.

4.4 Comparative Engine Tests at Ontario Research Foundation

During the demonstration period the interest in pollution control heightened and stringent new standards were set by the U.S. Environmental Protection Agency (EPA) for buses brought into operation in 1991. It is believed that the new U.S. standards will be adopted in Canada at about the same time, and that the use of gaseous fuels and perhaps methanol can provide a lower cost route to achievement of the new standards than modification of diesel engines and fuel. The Iveco CNG engine was designed for the earlier standards and, although capable of meeting the 1991 particulate emission levels, may require extensive modification (perhaps involving the addition of exhaust treatment devices such as 3-way catalyst systems) to meet 1991 standards for nitrogen oxides, unburned hydrocarbon and carbon monoxide.

After preliminary work on the testing of the DDA 2-stroke and the Iveco 4-stroke diesel, further testing was undertaken at the Ontario Research Foundation (ORF, now ORTECH). The tests compared the CNG engine with the 2 diesel engines, a propane engine, a spark-ignition methanol engine from M.A.N. (W. Germany) and another 4-stroke diesel engine, also from M.A.N.

Details of the data generated to date are recorded in the Appendix. Those relevant to the CNG bus can be summarized as follows:

I. Steady State Tests (Characterization)

Mapping of performance of the engines using the dynamometer confirmed that the Iveco CNG and diesel engines and the DDA 2-stroke engines would be expected to provide comparable performance under bus service conditions.

II. ADB Cycle Tests

The dynamometer was programmed to simulate the ADB test cycle and measurements made of the energy efficiency and exhaust emissions of the engines over this cycle. No attempt was made in these runs to optimize the performance of the engines.

The conclusions drawn on energy efficiency measurements are:

- the Iveco 4-stroke diesel engine exhibited the highest energy efficiency when operated over the ADB cycle
- the energy efficiency of the DDA 2-stroke diesel and the Iveco spark-ignition CNG engine were lower, but similar as shown in Exhibit 10.

Exhibit 10
Efficiency Measured in the ADB Cycle Tests

	Energy Efficiency, %	Efficiency Relative to DDA 2-stroke, %
Iveco 4-stroke diesel (with reverse rotation)	36.2	116
Iveco 4-stroke S.I. CNG engine	29.55	95
DDA 2-stroke diesel	31.1	100

It may be noted that the ORF dynamometer tests do not agree closely with fuel consumption measurements made in the road tests in Hamilton. The road test indicated that the CNG engine was more energy-efficient than the DDA 2-stroke engine (by about 3%). The tests on the Iveco diesel-engined bus and the DDA bus in Hamilton gave similar efficiency results to those obtained at the ORF dynamometer: the Iveco diesel-engined bus had an 8% energy advantage over the DDA bus in these measurements. These results indicate that direct comparison cannot always be made between in-bus road tests and tests obtained on an engine test stand. The conclusions drawn on the exhaust emission measurements are summarized in Exhibit 11.

The key conclusions were:

- particulate emissions measured on the CNG engine during the ADB cycle test were only 16% of those measured in the exhausts from the DDA and Iveco diesel engines

- at the given engine settings the NOx emissions of the CNG engine were almost twice those of the diesel engines

- at the given engine settings the level of unburned hydrocarbon emissions of the CNG engine was somewhat higher than the Iveco and the DDA diesel engines, however, the low reactivity of the CNG exhaust hydrocarbon (mainly methane) compared to that from the diesel engine reduces the significance of the CNG exhaust hydrocarbon level

- the carbon monoxide emissions level of the Iveco CNG engine was lower than that of the diesel engines.

For comparison purposes only, the 1991 EPA emission standards are also listed in Exhibit 11.

Exhibit 11

Emission Test Results Comparison

(grams/brake horsepower hour)

	Particulates	NOx	Unburned Hydrocarbon	Carbon Monoxide
DIESEL ENGINES				
DDA 2-stroke	0.17	10.8	1.4	1.9
Iveco 4-stroke	0.21	9.2	1.0	2.0
SI CNG ENGINE				
Iveco 4-stroke	0.03	17.0	1.6	1.3
FOR COMPARISON				
1991 EPA Emission Regulation for Buses - Maximum Value	0.1	5.0	1.3	15.5

Notes: The tests were conducted using the ADB cycle and not the EPA heavy duty vehicle transient cycle specified in the EPA emission standards.

The unburned hydrocarbon is controlled to reduce the ozone burden.

The unburned hydrocarbon in the CNG vehicle exhaust is principally methane which has a low reactivity in the production of ozone.

Source of measurements: ORF contract

It should be noted that the CNG engine emissions can be substantially modified by changing the engine settings and that since the EPA and ADB cycles differ, the comparison between the forthcoming EPA standard and the ADB cycle test results should be interpreted with caution.

Discussions with 3 CNG engine suppliers (M.A.N., Daimler-Benz and Iveco/Dereco) and with experienced test laboratories (ORF and the TNO Road Research Laboratory in the Netherlands) led to the following conclusions on exhaust emissions:

- the spark-ignition naturally-aspirated CNG engine will have no difficulty in meeting the 1991 particulate emission level

- although variations in the air-fuel ratio and the ignition timing can be used to optimize the gaseous emissions, NOx, hydrocarbon, carbon monoxide, within acceptable engine output and exhaust gas temperature levels, it is unlikely that conditions can be found in which the current CNG engine can be efficiently operated within the 1991 EPA specification without electronic controls and/or exhaust aftertreatment

- exhaust aftertreatment similar to that employed in gasoline engines offers an excellent prospect of meeting the 1991 emission requirements in heavy duty bus engines operated at close to the stoichiometric air-fuel ratio. Three-way catalyst systems using measurement of oxygen in the exhaust gas coupled with electronic engine control have already been adapted for use in CNG buses and the reported results are compared with the 1991 EPA requirement in Exhibit 12.

Exhibit 12

Emission Control in CNG Bus Engine*

(GM454 engine and 3-way catalyst tests at EPA)

Emissions (g/bhph)	CNG Bus with Pollution Control	1991 EPA Standard
Carbon monoxide	10.6	15.5
Total hydrocarbons	1.2	1.3
Nitrogen oxides	1.4	5.0
Particulates	0.02	0.1

* The GM454 engine is incorporated in Orion CNG buses supplied to Mississauga and Brooklyn Union Gas.

Further work was conducted at ORF to optimize the fuel economy/pollution control of the Iveco CNG engine. The ORF work included the development of a leaning device (providing a high air/fuel ratio) which, however, was unable to reduce the NOx level to the 1991 standard. Alternative emission control strategies involving turbo-charged lean-burn engine techniques in a different engine are under investigation at ORF.

4.5 CNG Bus in Perth, Australia

After the HSR road tests were complete, data was published on the testing of a CNG transit bus in Perth, Australia. The bus engine was a turbo-charged spark-ignition engine converted by Daimler-Benz from a conventional turbo-charged Daimler-Benz 4-stroke pancake diesel engine using a 2 level air/fuel control technique (stoichiometric switched to lean-burning) designed for minimum CNG consumption.

The test results reported the diesel powered bus to have a fuel economy of 55.3 litres/100 km compared to 42 m3 of gas/100 km for the CNG bus. No measurements of emissions were reported on the Perth bus, but Daimler-Benz have stated that they would probably adopt a stoichiometric air/fuel and exhaust aftertreatment technology if their engine were to be equipped to meet the 1991 EPA bus standard.

Comparison of the Perth and Hamilton test results are given in Exhibit 13.

Although there may be differences in the comparison of the gas in Perth and Hamilton, the data indicates that the fuel economy of the Hamilton buses (and the Iveco CNG engine) can probably be improved by turbo-charging, electronic control of air/fuel ratio, and other technical changes.

Exhibit 13

Comparison of CNG Bus Tests

	Perth	Hamilton
Diesel bus fuel consumption (litres/100 km)	55.3 (4-stroke)	52.6 (2-stroke)
CNG bus gas consumption (m3/100 km)	42 (4-stroke)	59.4 (4-stroke)
Fuel utilization ratio (m3 gas/litre diesel)	0.76	1.13

Perth data from J. Noon and Daimler-Benz; Hamilton data from Go/No-Go road test. Gas composition in Perth not specified.

5. CNG BUS FLEET OPERATION

5.1 Facilities and Services

Six buses were converted by HSR staff: one late in 1985 (the prototype for acceptance tests), 3 in 1986 and 2 in 1987. The buses provided a total of 99 bus months and 248,000 km of service in the 31 month period from December 1985 to June 30, 1988.

One additional GM 1977 "New Look" bus was re-engined with a special Iveco 4-stroke diesel-fuelled engine but was found to be unsatisfactory and was therefore reconverted to the original 2-stroke configuration after 10 months of service.

The technology for the in-house conversion and reconversion of buses to CNG, 4-stroke Iveco and 2-stroke DDA engines is therefore established at HSR. All CNG bus tests, maintenance and repair requirements were met by existing HSR staff. Driver training and revenue service operations were conducted with the existing HSR staff. A technician was assigned full-time to oversee maintenance, tests and setup of the CNG bus fleet.

The compressor-refuelling station was installed at the Wentworth Street garage and at June 30, 1988 had operated without major incident for 24 months during which time approximately 135,000 m3 of gas had been compressed and transferred to the CNG buses. Bus fuelling during the start-up period used CNG purchased from a nearby commercial CNG refuelling station operated by Union Gas.

The compressor at the Wentworth Street garage is the property of Union Gas who provided the engineering design and advice on the installation and technical service. HSR staff is now experienced in the procedures necessary for the refuelling of CNG buses and the daily maintenance of the refuelling facility.

5.2 Bus Availability and Kilometrage

Exhibits 14 and 15 summarize the CNG fleet size and kilometers of service provided in the 17 month period from February 1987 to June 30, 1988, which accounts for 91 bus months of service over 173,725 km (70% of that recorded in all 3 phases of the demonstration).

The fleet kilometrage summarized in Exhibit 14 shows a wide variation over the period. The variations illustrate the effect of bus availability (number converted), the high winter demand for all buses and the effect of the bus dispatchers' selection (reduced use of the CNG fleet) which resulted from range problems encountered in the winter months (see fuel consumption and refuelling discussions in Section 5.4).

Thus the peak monthly service (13,800 km/month) was obtained with 6 buses in service but this was reduced (to the 10,000 km/month fleet level) in March-June 1988. The average monthly service to date increased to the 10,000 km level.

Exhibit 15 presents the kilometrage data on an average bus basis showing that the average level over the 17 month period was 1,910 km/month/bus but that a level as high as 2,270 km/bus/month and as low as 1,570 km/bus/month were recorded. The average of 1,910 km/month CNG bus over the 17 month period can be compared with the diesel fuel average of over 5,000 km/month/bus, which indicates that technical factors and bus selection currently limit the utilization of the CNG fleet.

5.3 Fuel Consumption

The carefully measured fuel consumption of the prototype CNG bus (#7727) in the Go/No-Go road acceptance test was 57.5 m3/100 km.

Exhibit 14

CNG Bus Fleet Service

(km/month total fleet)

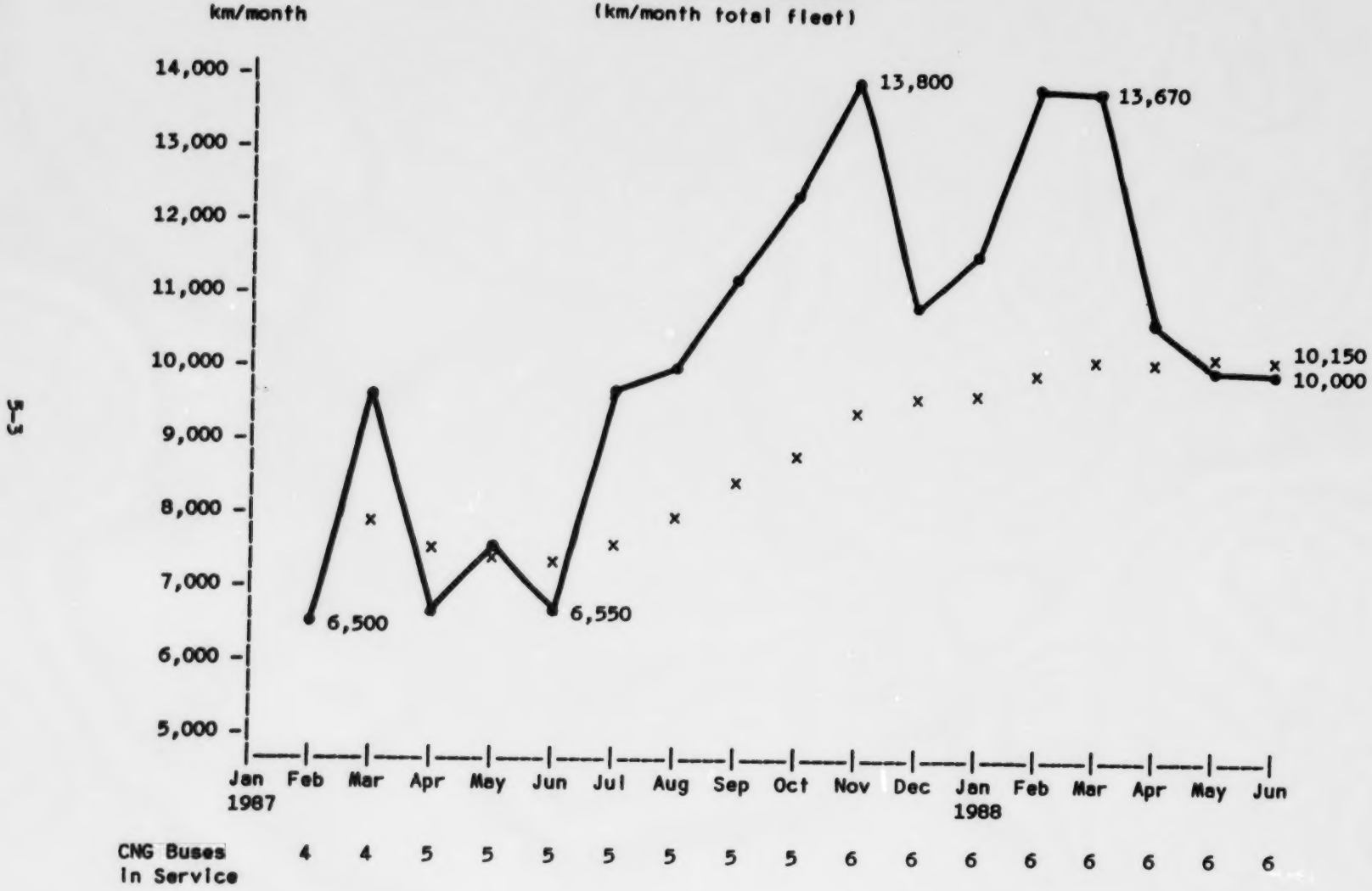
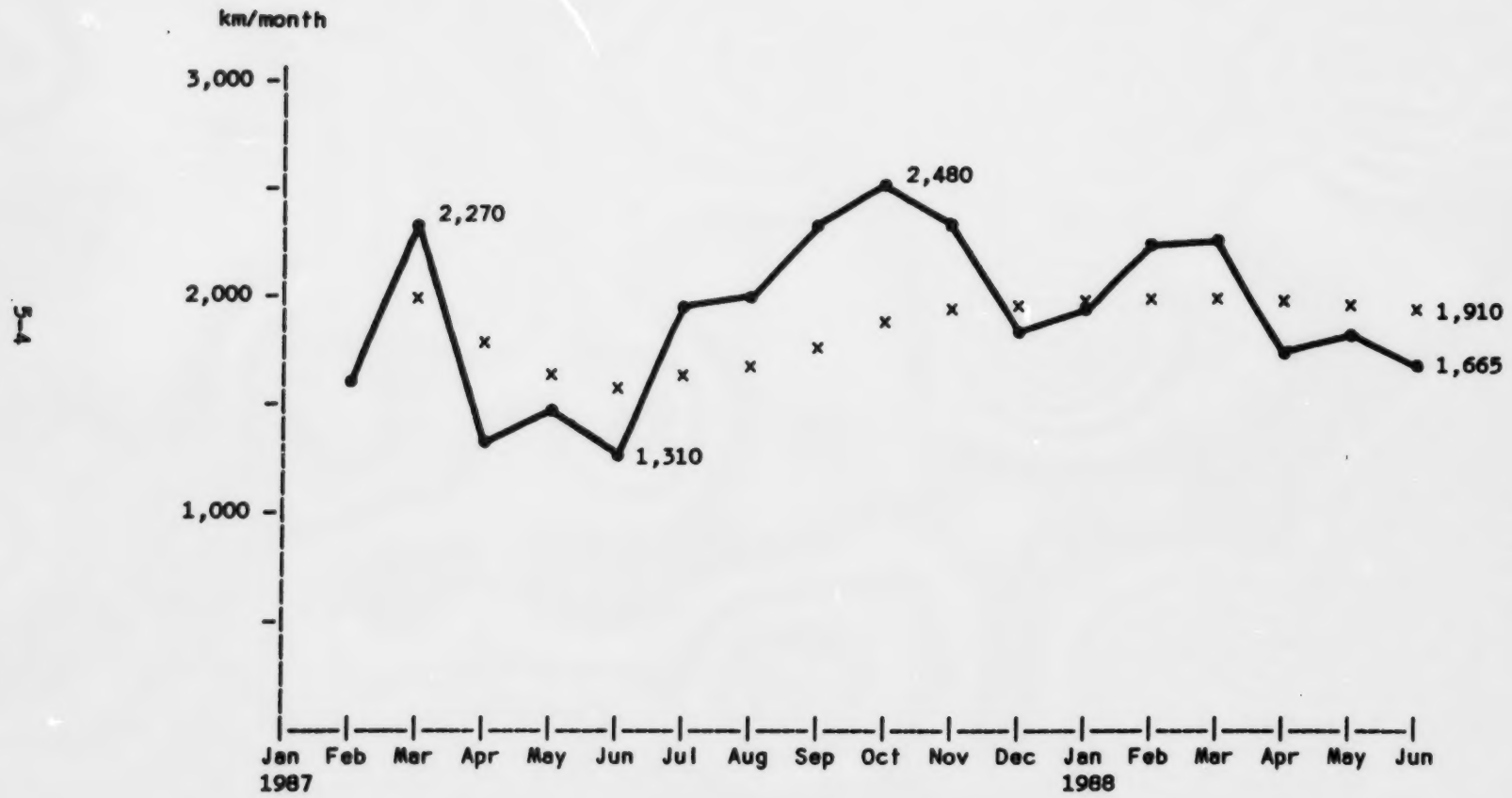


Exhibit 15

Average Service per Bus per Month



Other values obtained with the bus fuelled at the commercial CNG station in the period November and December 1985 were significantly different at 48.9 m3/100 km and 50.3 m3/100 km respectively. Fuel consumption of other buses fuelled at the commercial CNG station (where fuel loaded was metered) also gave unreliable values. Accordingly the fuel consumption volumes reported are only those of the CNG fleet when refuelled at the Wentworth Street garage. The fuel measured was that supplied to the compressors and therefore includes losses in compression and refuelling.

The gas consumption recorded over the 17 month period ending 30 June 1988 are shown in Exhibit 16 over which period the average of the CNG fleet was 76.8 m3/100 km, 53% higher than that recorded in the road acceptance values in the Go/No-Go test. As seen in Exhibit 16, the fleet average gas utilization was high in the winter and lower in the summer but fuel use in 1988 was substantially higher than in 1987. The peak consumption was reached in March 1988 when fuel consumption was 96.9 m3/100 km - almost double that recorded in the acceptance test and 41% higher than the maximum acceptable value in that test.

The high winter fuel consumption values may be due to excessive idling of the CNG buses particularly at the start of the shift. The overall high fuel consumption may be due to an over-rich air/fuel mixture (incorrect set-up of the bus engines and/or mixture enrichment due to vibration and the change in setting of the mixture screw on the CA 425 air/fuel mixer; the drift was encountered in the bus fitted with the 200D mixer). High fuel consumption may also be due to compressor and refuelling spills. Fuel consumption may also have been increased by minor compressor and refuelling spills.

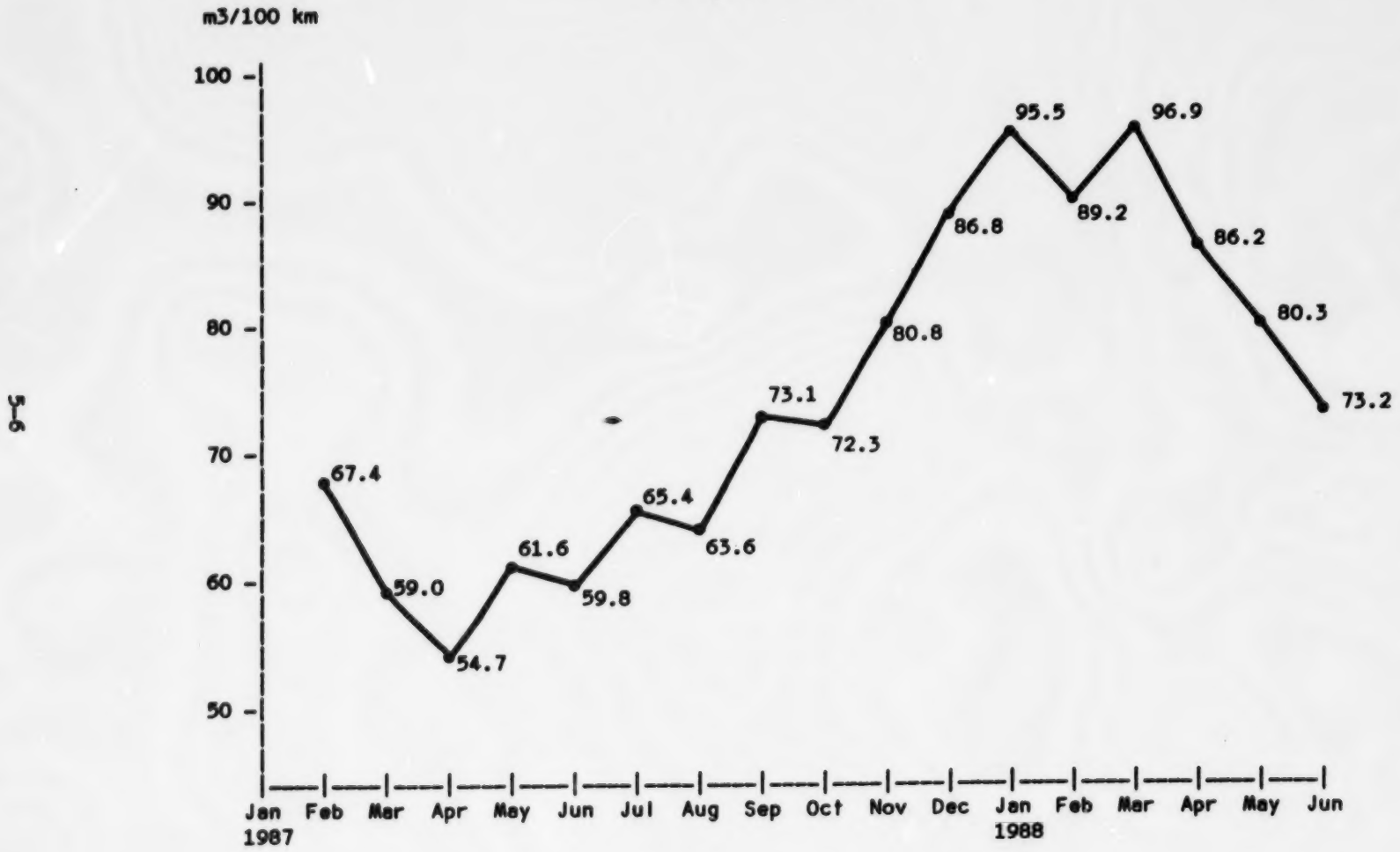
The fuel consumption measurements indicate the need for:

- means to measure the actual fuel dispensed to the buses
- reconsideration of the engine set-up procedure

Exhibit 16

CNG Fleet Fuel Economy

(average for fleet)



- use of mixers (such as the Impco 200D) which maintain a constant air/fuel ratio in service
- evaluation of indoor parking of CNG buses in winter to reduce the fuel used to warm-up the bus (as distinct from that used for bus propulsion)
- other measures to improve the fuel economy of the CNG bus such as engine turbo-charging or increase in the compression ratio.

5.4 Bus Range

The Go/No-Go test on the prototype bus indicated that the CNG buses with a 7 aluminum gas storage tank configuration would provide a maximum range between refuelling of 375 km. A number of instances were encountered when the CNG buses ran out of fuel while in service and had to be towed back for refuelling.

The suspected causes may be:

- Underfuelling of the buses due to incorrect compensation for the temperature increase involved in compression of natural gas. As is current practice in the industry, a sensor is used to measure the ambient temperature (rather than the temperature of the CNG storage tank) and the intake temperature of the compressed gas. If the temperature compensation setting ("dome load") is too low, premature shut down of the refuelling compressor occurs. This was observed and corrected.

- Cylinder shut off. At least 2 instances of employee error were found where one or more of the on-vehicle CNG storage cylinders had been isolated by shutting off a valve.

- Excessive fuel consumption reduces vehicle range. For example at the peak fuel consumption of 96.9 m3/100 km encountered in March 1988, the vehicle range would be reduced to 195 km - about 52% of

that estimated from the road acceptance test. It is possible that vehicle underfilling combined with high fuel consumption could occur together reducing the range to unacceptable levels.

The best resolution of the range limitation appears to be to reduce the fuel consumption of the buses. Other measures include the use of higher capacity or more fuel tanks (it is possible to increase both the diameter and length of the storage cylinders perhaps to provide the long term range requirement of 450 km but this will further increase the bus weight) and resolution of the tank overfilling problem.

It was noted that the 40 ft. diesel buses at HSR are refuelled daily and in 1987 required an average diesel fuel refill of 110 litres (corresponding to a range of 191 km in the 1977 vintage GM buses). In one 1987 instance the fuel required at a diesel bus refill was 286 litres (corresponding to a range of about 500 km). Only 8% of the diesel bus trips recorded in 1987 equalled or exceeded 375 km.

5.5 Problems Encountered and Solutions

5.5.1 Engine Related Problems

The Iveco CNG engine is not yet a series production item and the HSR demonstration was the first use of this engine. The performance achieved under these circumstances is excellent and can be improved in the future by incorporation of a number of new features many of which can be based on the results of the HSR demonstration. These would improve engine component durability and reduce bus down-time for maintenance.

Principal problems encountered with the engine can be traced to:

1. The lack of experience with accessories for conversion of a heavy duty high gas consumption engine to meet the rugged transit bus

environment and Canadian winter conditions. The most appropriate gas regulators, mixers, spark plugs and other components of the ignition system and various components of the engine coolant system may not have been selected for the service conditions encountered.

ii. The effect of high engine temperatures on plastic and certain metal components.

High engine temperatures, low winter ambient temperatures and extensive CNG component wear were a frequent cause of problems (see Exhibit 17).

Most frequent problems were:

Regulators: The first CNG engine was equipped with 3 regulators which restricted gas flow to the mixer during cold start due to low outlet pressure. They were replaced by a combination of 2 regulators (a NZIG high pressure and an impco low pressure regulator) which delivered a higher pressure to the mixer.

Air/fuel Mixer: The mixer had difficulty in maintaining settings and gas valve passage wear was excessive on one bus. A model suitable for heavy duty service is on test (impco model 2000).

Spark Plug Tubes: Removal of spark plug loosened tubes which then leaked coolant into the engine. Use of a special holding tool at each spark-plug change and replacement of washer and seals when tubes are serviced eliminates this problem.

Spark Plug Boots: Phenolic covers for spark plugs deteriorated in the hot engine compartment causing spark plug failure. Silicone wire sets solved the problem.

Exhibit 17
CNG Bus and Refuelling Problems and Applied Solutions

	PROBLEM	SOLUTION
ENGINE RELATED	Starting failures in cold weather	Regulator problem. Replaced 2 parallel Tartarini regulators with NZIG and Impco in series
	Drift in settings and valve wear	Mixer unsuitable. Larger unit on test in one bus
	Engine failure	Valve keeper failed: rebuilt in-house
	Short life of starter	Bosch starter should be replaced with longer life unit designed for 12 volt use
	Engine speed governor failure	Limitron prevents damage. Need electronic governor
	Engine overheated due to improper fan operation and undersized radiator	Rewired contacts to have fan on full time. Increased capacity radiator has been designed
	Spark plug life	Improve thermal environment
	Spark plug boot failure	Replaced phenolic type boot with silicone wire sets
	Coolant leakage past spark-plug tubes	Special tool for removing spark plugs. Use of non-replaceable washers, O rings
	Non starting	Improve maintenance of battery, ignition wiring
	Inadequate power	Improved set up using 4 gas analyzer

Exhibit 17 continued

FUEL STORAGE SYSTEM RELATED	Insufficient gas stored in bus	(Proposed solutions: Improved fuel economy, larger tanks). Modify dome load sensor and training
	Restriction of use of aluminum cylinders by Fuels Safety Branch, Ontario	Solution introduced rapidly by industry and B.C. Research Council
	Minor leaks	Reduced with improved specification components and experience in fitting
BUS RELATED	Stiff steering	Air-assisted steering introduced to offset added 400 kg bus weight (Classic GM bus has power steering)
	Loss of power, rough ride	Resolved engine problems
REFUELLING	Drive-away while fuel hose connected	Make hose visible to seated driver (Proposal: use dedicated fast-fuelling system)
	Cycling of compressor	Maintenance minimizes dirt and freeze up
	Failure of seal at refuelling probe	Routine replacement of O ring seal at dispenser pistol
	Failure of relief valve	Redesign of relief valve by manufacturer

Starter: The electronic starter failed at the solenoid and switch. The problem was eliminated when engine fuel system changes reduced cranking time in cold start conditions.

Engine Failure: The cause was unknown but damage was limited by use of an engine speed limiter in addition to the supplied governor. Fast rebuild followed minor damage. (The failure was considered to be a manufacturing defect - the valve keeper grooves failed prior to use in revenue service and were replaced under the engine warranty. There was no evidence of engine overspeed and a material problem is suspected).

5.5.2 Fuel Station Problems

Excessive cycling of the compressor was encountered which was traced to dirt and/or freeze-up at low temperatures. Drive-away from refuelling with the hose still connected was another problem. The breakaway coupling and shut-off valve in the fuel line are designed to reduce fuel discharge from this hazard. A solution could be redesign to make the hose visible to the driver and/or use of a dedicated fast-fuelling system.

5.5.3 Tank Problems

Fire tests by the California manufacturer caused temporary restriction on use of aluminum cylinders (cylinders could be operated for a period only if fuelled to 50% or more of design pressure). Restriction lifted when new burst disk material was introduced. All cylinders in HSR buses are now fitted with the new burst disk (pressure and thermally sensitive so that the cylinder vents prior to annealing or weakening of the cylinder material).

5.6 Driver and Rider Acceptance

The drivers' responses to the CNG buses were monitored for a 2 month period and their comments sought throughout the demonstration. They are enthusiastic about the performance of the CNG buses. Reports cite such attributes as "no smelly fumes" (compared to diesel), "less noisy", "lots of power - very smooth running", and "smooth acceleration from stops and gear change".

The positive responses from drivers far outweigh the negative responses which are attributed to bus-specific maintenance problems which were resolved.

No adverse comments on the CNG buses were received from the public who were essentially unaware of the innovation despite the notices inside the bus (statement of demonstration) and the signage on the bus exterior ("I RUN ON NATURAL GAS").

5.7 Safety

A number of steps were taken to provide maximum safety conditions and prompt emergency response in the event of a CNG fire. These included:

- Training of refuellers, fitters and drivers in CNG safety. Included was certification of mechanics and a supervisor by the Fuels Safety Branch (Ministry of Consumer and Commercial Relations, Ontario) after a course at Centennial College and a written examination.

- Assistance was provided to fire departments in Hamilton in training of personnel on CNG. This included visits by CNG buses to 40 fire department sites in the area. The City of Hamilton prepared a training film on the subject of CNG.

- A bulletin on CNG safety was prepared for use in training HSR staff, equipment inspection and maintenance procedures.

A number of CNG spills occurred during refuelling but no fires, injuries or property damage occurred. As noted above, solutions to prevent recurrence of these incidents have been or are being implemented.

5.8 Conclusions on CNG Bus Operations

The HSR program has demonstrated that:

i. CNG buses provided a satisfactory level of performance compared to the diesel buses under the conditions of the demonstration.

ii. CNG is a technically viable fuel for use in transit buses in the future.

iii. In-house refitting of existing diesel powered GM buses with a CNG engine and fuel sytem has been shown to be a feasible but expensive route to the production of CNG buses.

iv. Public and driver acceptance of the CNG buses is not less than that of the diesel buses.

v. The safety record of the CNG buses and the refuelling facility was excellent. There were no major incidents.

vi. The availability of the CNG buses was comparable to that of the diesel buses but a higher level of maintenance effort is needed to reach that availability level.

vii. The utilization of the CNG buses was about one half that of the average in the diesel fleet due to concerns over the range of the

bus following occasions in the winter when CNG buses occasionally ran out of fuel while in service (attributed to underfuelling and high fuel consumption due to mixer malfunction).

viii. The performance of the CNG buses (with the exception of the current range limitation) was excellent. The acceleration, speed and route timing matched that of the best diesel buses in the HSR system including routes that contained a 7% grade. The particulate and odour levels from the exhaust were lower than that from current technology diesel buses, the CNG buses had a lower interior noise level than the diesel buses and other favourable ride quality characteristics.

ix. The cost of untaxed natural gas is low compared to the cost of taxed diesel fuel but the prospects for cost savings in the total system need verification.

x. Technical improvements have been defined which will improve the performance, durability, range and operating costs of CNG buses in the future. The improvements relate to the engine, fuel storage and the refuelling facility (see Exhibit 18).

xi. A series-produced CNG engine is required.

The demonstration did not clearly demonstrate the anticipated cost-effectiveness of CNG buses compared to diesel buses because of the experimental nature of the program. Individual bus monitoring and detailed data gathering procedures will be required to generate revenue service cost and system reliability information. The demonstration provided technical goals which if achieved will provide a cost advantage for the CNG buses.

Exhibit 18
CNG Bus System Proposed or Required Improvements

	REQUIREMENT	POSSIBLE METHOD
CNG ENGINE	Improve durability, reliability	Use heavy duty carburetion system. Involve carburetion system engine manufacturer in design, production
	Improve fuel consumption	Optimize combustion and electronic fuel controls. Improve engine set up procedure. Long term: use electronically controlled engine and/or higher compression ratio. Use heavy duty mixer
	Reduce gaseous emissions (NOx)	Use fuel management system with electronic ignition timing, exhaust gas and air fuel ratio feedback and 3-way catalyst system
	Simplify engine maintenance	Improve access to alternator, starter motor, mixer, ignition coil. Eliminate reverse rotation, mechanical governor, change alternator. Extend spark plug life, reduce temperature build-up in engine
	Improve performance	Increase maximum up to 210-220 (turbo-charged engine). Improve cold start (mixer/carburetor design). Improve engine diagnostic measurements
VEHICLE TANKS	Increase capacity for increased range and margin	Support development and testing of higher capacity and low weight cylinders
	Obtain fast approval for new designs	Support safety technology investigations at federal and provincial level

Exhibit 18 continued

FUEL STATION	Reduce refuelling time to 5 minutes	Increase compressor capacity. Gas utility supply of higher pressure gas at mains. Improve knowledge of gas transfer process and limitations
	Reduce maintenance requirement	Redesign fuel probe for reduced replacement of O ring. Select robust compressor designs. Develop preventative maintenance technology
	Continue current excellent safety record	Avoid drive away while hose coupled to bus through design of fuel dispenser/hose and more training of drivers and refuellers

6. ASSESSMENT OF CNG AND DIESEL BUS ECONOMICS

6.1 Diesel Bus

The current annual cost of operating a 40 ft. transit bus in the Hamilton area is $115,000 of which the cost of taxed diesel fuel is $12,540 (33,000 litres/year at 38 cents/litre which includes federal and provincial taxes of 18 cents/litre). Cost increases will be incurred in the future as the price of crude oil increases the cost of diesel fuel.

1988 diesel bus technology will be insufficient after 1991 to meet the new emission standards. After 1991 diesel buses will most probably require particulate traps which will increase the capital cost of buses (by $8,125 it is estimated) and maintenance costs. In addition diesel fuel costs will increase due to higher consumption when traps are used (6% increase estimated by engine builders). In Canada there may also be a requirement for a change in the specification of diesel fuel to provide low sulphur, low aromatic content diesel fuel which will be higher in cost that the current diesel fuel (4.8 cents/litre increase is estimated by Canada's oil refiners).

It is not known at this time whether the fuel quality improvement and use of traps will both be required to meet the 1991 EPA standard. Current work by engine manufacturers indicates that the standard might be met by 1994 with a change only in the fuel quality. The net effect of a requirement for a change in the fuel quality and use of traps will be that a 1990+ technology bus will cost $3,380 or so more a year to operate than a 1988 technology bus, even if the price of crude oil remains depressed at 1988 levels.

In the event that only a change in fuel quality is required (not achievable by 1991), the annual cost increase for a typical diesel bus would be $1900-1600 (with or without fuel tax respectively).

The effect of the anticipated diesel technology changes is illustrated in Exhibits 19 and 20 where the effect of fuel taxes and of increases in the price of crude oil are also considered.

6.2 CNG Bus

The costs involved in the CNG bus demonstration at HSR are not typical of those expected in future revenue service, due to the low utilization rate, high conversion investment and maintenance costs, and the short operating life of the retrofitted used diesel buses employed in the demonstration. Accordingly, estimates have been made of the capital and operating costs of new factory-produced CNG buses. The costs of such buses are compared below with the anticipated costs of post-1990 diesel buses equipped with particulate traps and fuelled with a low sulphur, low aromatic diesel fuel.

Estimates of the cost of operating factory-produced CNG buses in the future are illustrated in Exhibits 19 and 20, at 2 levels of CNG refuelling technology (and cost), with and without the 8% Ontario sales tax and under conditions where the wholesale price of natural gas (in Alberta) escalates in parallel with increases in the international price of crude oil.

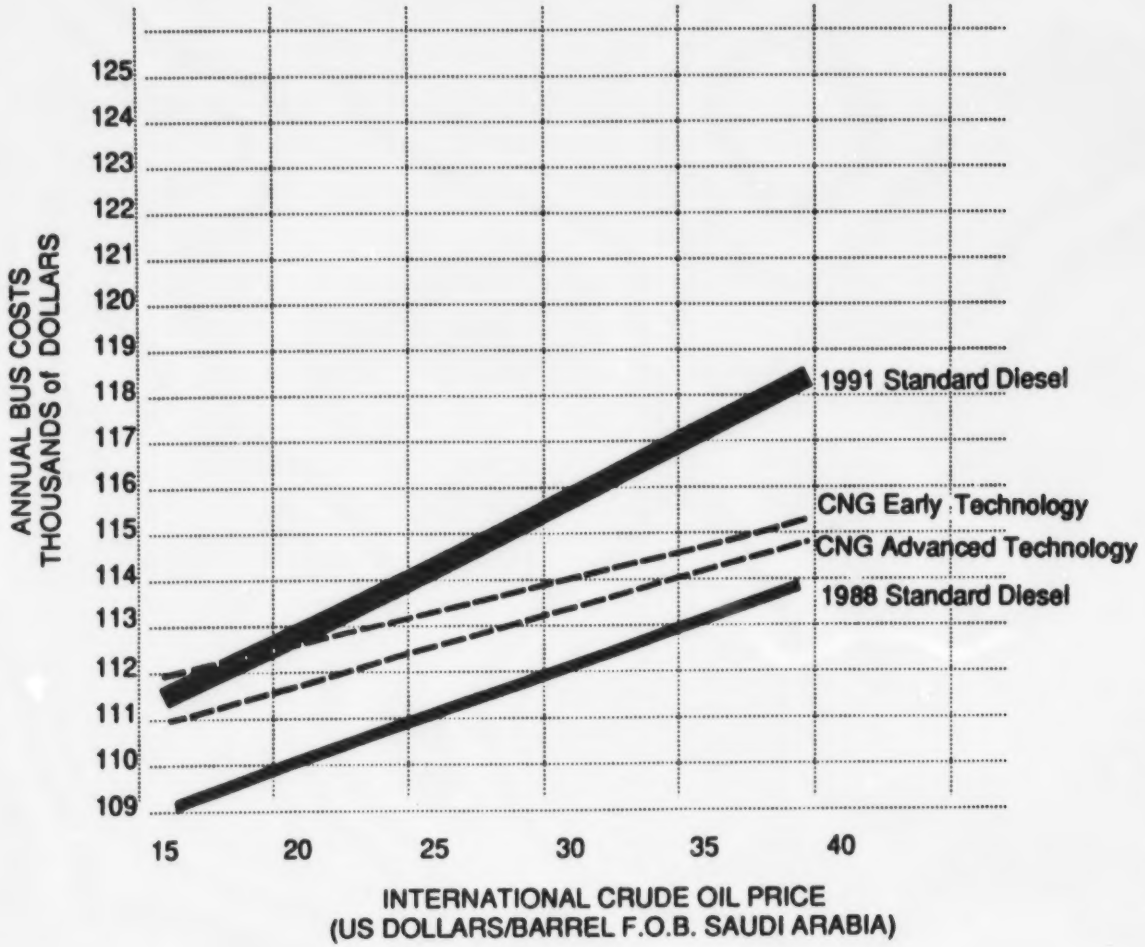
6.3 Conclusions

The principal findings using the above assumptions are:

1. The annual costs of CNG buses are estimated to be lower than those of diesel fuelled buses if diesel fuel is taxed. The cost savings for CNG will be substantially increased when the 1991+ technology diesel buses are introduced and even further increased when advanced CNG bus refuelling technology is available. The cost savings will be particularly significant if both traps and revised quality diesel fuel (low sulphur, low aromatics) are required.

Exhibit 19

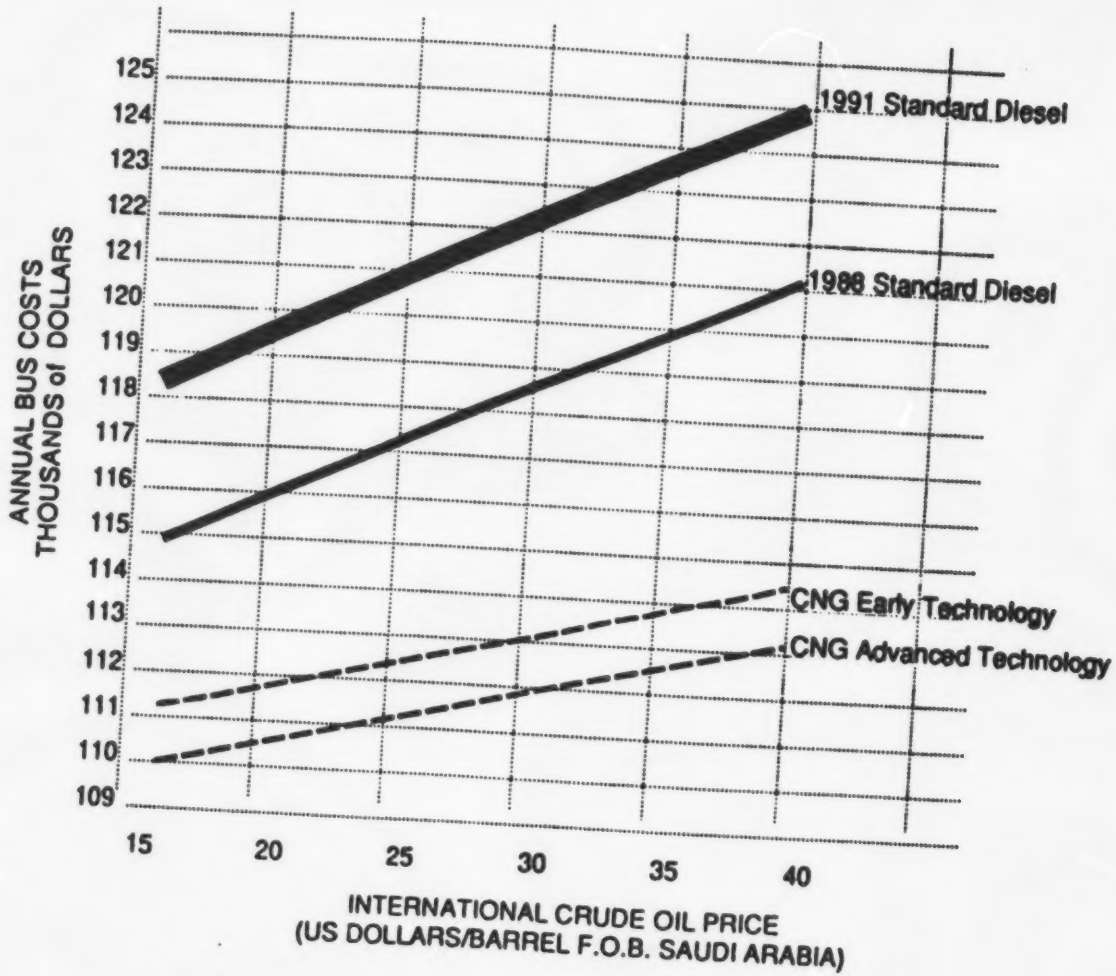
Comparison of Annual Operating Costs of City Bus, Diesel Untaxed



Note: CNG no conversion subsidies, no tax on fuel. Assumptions given in Exhibits 21 and 22.
1991 diesel standard cost includes traps and diesel fuel quality changes.

Exhibit 20

Comparison of Annual Operating Costs of City Bus, Diesel Taxed



Note: Diesel taxed @ $0.18/litre. CNG conversion subsidies and no fuel tax. Assumptions given in Exhibits 21 and 22.

1991 diesel standard cost includes traps and diesel fuel quality changes.

2. CNG buses with factory-built emission controlled engines will be competitive with 1991+ technology diesel buses (equipped with traps and using a low sulphur, low aromatic diesel fuel), even if no fuel or sales tax advantage applies to the CNG bus when the international price of crude oil exceeds US$18/barrel.

3. Factory-produced CNG buses with emission controlled engines will be competitive even with 1988 technology diesel buses and no tax advantage when the international price of crude oil exceeds US$28/barrel.

4. The cost savings from CNG use are expected to be higher when factory-equipped new CNG buses are brought into service than when existing buses with a shorter life expectation (than the 18 year life of a new bus) are converted. Components of the CNG bus cost analysis are summarized in Exhibits 21-23.

Exhibit 21

Comparative Bus Cost Analysis

	INVESTMENT	COST PREMIUM (PER BUS BASIS)
CNG BUS (with fast-fill refuelling)	Bus premium	Premium over 1991 6V92T: $15,050
	Fuel station/garage	Premium $35,000 (early refuelling technology) Premium $23,300 (advanced refuelling technology)
DIESEL (1988 vs 1991+)	1991 Standard bus premium	Increase for 1991+ standards: - trap system $8,125 + 6% annual maintenance cost - fuel economy reduced by 6% - low sulphur, low aromatic fuel at 4.8¢/litre premium
NATURAL GAS (for export from Alberta)		Escalated at 100% of crude oil rate

Exhibit 22

Future CNG Costs in Hamilton

		CENTS/1000 FT3	CENTS/M3
UNCOMPRESSED GAS COST (CRUDE OIL AT $16/BARREL)	Alberta price	150.0	5.30
	Pipeline tariff to city gate	72.2	2.55
	Local distribution cost plus incentive	149.8	5.27
	Price to refuelling station	372.0	13.12

		CENTS/LITRE DIESEL EQUIVALENT
	Price to refuelling station	14.83

		50 BUS FLEET EARLY TECHNOLOGY COMPRESSION	100 BUS FLEET ADVANCED TECHNOLOGY COMPRESSION
		CENTS/LITRE DIESEL EQUIVALENT	
GAS COMPRESSION COSTS AT BUS FLEET LOCATIONS	Compression, storage, equipment	5.35	3.57
	Compression rebuild	0.67	0.45
	Other maintenance and labour	4.98	3.32
	Utilities	0.84	0.84
	Service station cost	11.84	8.18
	Pump cost, ex taxes	26.67	23.01
BUS EXPENSE	Premium over diesel bus amortized*	2.53	2.53
	Added maintenance	1.37	1.37
	Subtotal bus expense	3.90	3.90
TOTAL COST		30.57	26.91

* excludes vehicle sales tax rebate currently available in Ontario

Exhibit 23

Comparative Annual Bus Operation Cost

(Thousands of dollars)

		CRUDE OIL PRICE (US DOLLARS/BARREL)	
		$16	$40
DIESEL BUS	1988, taxed	114,900	121,100
	1991+,taxed	118,300	124,900
	1988, untaxed	109,000	115,200
	1991+, untaxed	112,000	118,600
CNG BUS	Early technology (1)	112,000	115.050
	Advanced technology	100,900	113,800

(1) Omits Ontario sales tax credit of $16,040/bus ($890/year credit)

7. INFORMATION TRANSFER AND PUBLICITY

Copies of the contracts, minutes of meetings, technical reports and papers on the HSR demonstration are contained in the Appendix.

7.1 Meetings of the Steering Committee and Technical Subcommittee

Minutes of all meetings were issued to Steering Committee members and other attendees.

Twenty-two meeting of the Steering Committee were held in the period Feb. 26, 1985 to May 19, 1988.

Three meetings of the Technical Subcommittee were held.

7.2 Technical and Progress Reports

Three interim progress reports and a final report on the project were issued to Steering Committee members and project sponsors.

The Technical Reports issued were:

1. Demonstration of the Use of CNG as a City Bus Fuel, (Project Description), Sept. 1984
2. Safety Aspects of CNG Use at HSR, Apr. 1985
3. Report on Demonstration Project for CNG as a Transit Bus Fuel, June 1985
4. Demonstration Data System, (proposed), July 1985
5. Technical Specifications for CNG Engine and Related Contracts, July 1985
6. Engine Performance Report, (Dereco), Aug. 1985
7. NGV Bus Demonstration: Engine/Bus Acceptance Tests, Nov. 1985
8. Summary of Investigation of European Gaseous Fuel Engines and Compressors, Dec. 1986

9. Expanded Use of Natural Gas Buses at HSR, May 1987
10. ORF Presentation to Steering Committee on Engine Tests, June 1987
11. Notes on Crash Tests of NGV Buses
12. Performance and Emissions of Propane, Natural Gas and Methanol Fuelled Bus Engines, Mar. 1988
13. The Demonstration of Natural Gas Fuelled Buses in Revenue Service at HSR, (proposal for Phase 4), June 1988

7.3 Internal HSR Records

Weekly summaries were prepared on the kilometrage of each bus, the fleet consumption of natural gas and of maintenance and repairs conducted on the CNG buses.

Driver comments on the CNG bus performance were recorded for 2 months (April-May 1986) in "Operators Daily Report on NG Buses". A similar report was prepared on the 4-stroke diesel bus.

Special reports were prepared on long distance trips to Toronto, Ottawa, Indianapolis and New York City.

7.4 Papers and Presentations

June 1985: Report on Demonstration given at Ontario Natural Gas for Vehicles Conference (R. Duncan, B. Rogers)

Feb. 1986: Progress Report to S.W. Ontario Transit Managers Workshop, Chatham, Ont. (B. Rogers)

Apr. 1986: Status Report on CNG and Propane Buses at OUTA meeting, Oakville (R. Duncan, W. Jenkins - OC Transpo)

June 1986: CNG and Propane Buses at Gaseous Fuels Conference, Vancouver/Expo 86 (R. Duncan, W. Jenkins, R. Webb)

Nov. 1986: Status Report, CUTA Annual General Meeting (R. Duncan, B. Rogers)

Mar. 1987: CNG Bus Demonstration Report, APTA Annual General Meeting, Jacksonville, Fla. (R. Duncan)
Methodology for Demonstration Projects, APTA, Jacksonville, Fla. (R. Webb)

June 1987: CNG and Propane Bus Report, Joint US DOE/Canada Workshop on Alternative Fuels, Windsor (R. Duncan, W. Jenkins, R. Webb)
CNG, Propane and Methanol Bus Engines Performance and Emissions (W. Goetz, D. Petherick, T. Topaloglu)

Sept. 1987: CNG Bus Status at "On the Road with Natural Gas" Conference, Minneapolis, Minn. (R. Duncan)

Mar. 1988: "CNG, Propane and Methanol Bus Engines," SAE paper presented Detroit, Mich. (W. Goetz, D. Petherick, T. Topaloglu)

7.5 Video

A video was prepared on the HSR CNG bus demonstration (Apr. 1988).

7.6 Other Events/Publicity

1. Official opening of demonstration and press conference, by Chairman, Hamilton-Wentworth Regional Council, Oct. 29, 1986
2. Open House, Oct. 1987
3. Bus demonstrations:
   Energy 2000 Conference Toronto Nov. 1985
   American Public Transit Assn. meeting, Ottawa, May 1986
   New York Energy Commission (NYSERDA)
   American Gas Assn. meeting, Minneapolis, Sept. 1987
4. Visit by a group from Steering Committee members to Daimler-Benz, M.A.N., Fiat (CNG engine developments), Nuovo Pignone (compressors), Daimine and Faber (CNG cylinders) and commercial refuelling stations in N. Italy, Sept. 1986
5. Visit by R. Duncan and T. Topaloglu to Thailand at invitation of Petro-Canada and Nova Corporation.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

1. The technical feasibility of operating CNG transit buses has been established.

2. The technical feasibility of converting GM diesel buses to the use of CNG has been demonstrated.

3. The safety record of the CNG buses and the refuelling station was equivalent to that in the diesel bus operation at HSR. (Note that the CNG buses were stored outdoors and information is being sought on the safety implications of indoor parking).

4. Total costs in the demonstration period did not provide a cost advantage over that of the existing diesel buses. However, fuel consumption tests have indicated that CNG may offer cost advantages in the future.

5. The demonstration defined engineering and equipment changes, which if implemented, could provide a level of service comparable to that of the diesel bus fleet and costs lower than those now experienced with the diesel buses.

6. Engine tests have shown that the CNG bus has a lower level of particulate emissions than the diesel.

7. Production model (series-produced) CNG bus engines with emission controls are likely to be cost-competitive with emission controlled (post-1990 standard) diesel engines.

8. It is most likely that CNG buses will be more cost-effective than diesel buses when buses must conform to the post-1990 EPA emission

standards.

9. The competitiveness of the CNG bus will be increased if design features are included in the manufacture which will improve component durability and reduce the frequency of maintenance.

10. The prospects for substitution of CNG buses for diesel will be increased if the range limitation of the CNG bus can be eliminated. Processes for increasing CNG bus range have been identified.

8.2 Recommendations

1. The improvements defined in the demonstration should be verified in a 2-year demonstration in which CNG buses are operated in revenue service.

2. The goals of the revenue service demonstration should include: demonstration of attainment of the post-1990 NOx and other emission standards; a high bus refuelling rate comparable to that within the diesel refuelling system, and a CNG bus range of at least 400 km.

3. The revenue service demonstration should include a data gathering and analysis process which will provide a quantitative comparison of the cost of acquisition, fuelling, operation and maintenance of each CNG and diesel-fuelled bus in the demonstration and assistance in trouble shooting.

4. The full time services of a technician should be included in the demonstration to coordinate and support the general maintenance and other services provided by HSR in support of the revenue service activity.